Calculation of mechanical stress and deformation of support structure and coils of the COMPASS-Upgrade tokamak (v 10.1)

Zpracování výpočtu mechanického napětí a deformací v nosné kostrukci a v cívkách tokamaku COMPASS upgrade (verze 10.1)“

1. Scope

The aim of the calculation is to provide coupled electromagnetic (EM) and structural analysis of the behaviour of the COMPASS-U support structure in the current state of design under the specified conditions. The calculation should allow extensions and part design modifications that are going to be supplied later.

The EM part of the analysis should provide magnitudes and resulting directions of forces acting on the coils and the support structure elements. EM model will consist only of the poloidal and toroidal field coils and plasma column (modelled as conductive torus at specified position) and currents flowing through these elements.

The EM model can be run as a magnetostatic calculation. The inputs for the EM model will be the values of currents in the poloidal and toroidal field coils, plasma current and position of the plasma column and will be delivered in a separate file.

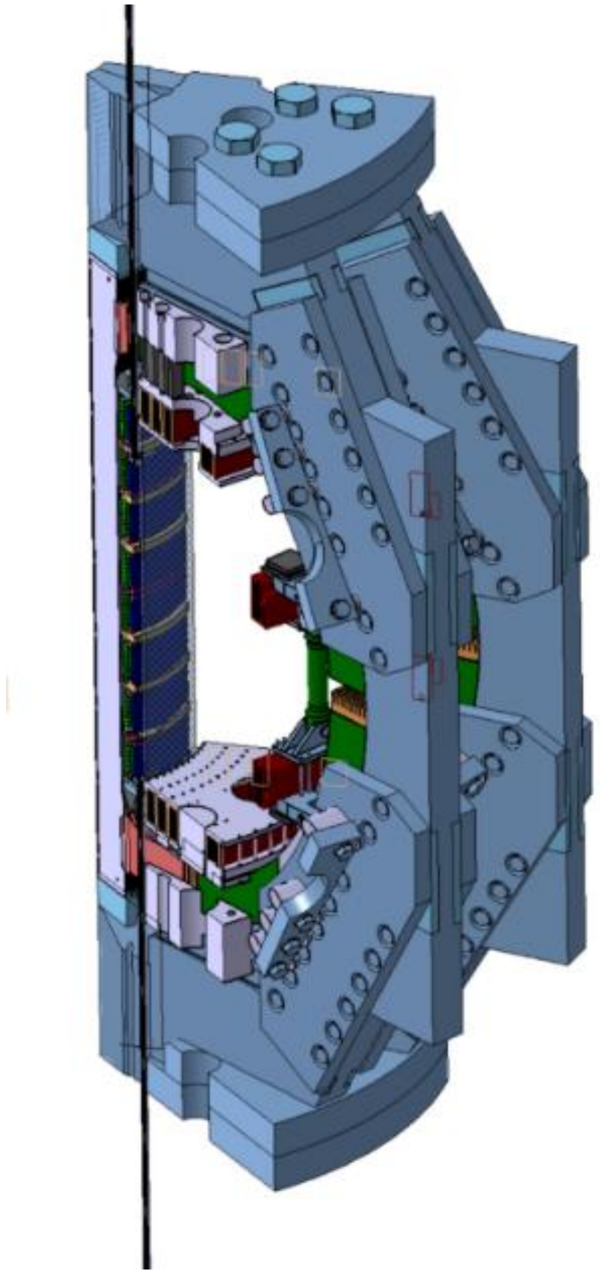
The support structure of the Compass-U tokamak is designed to withstand tremendous forces during the tokamak operation. These forces arise from the interaction of currents and magnetic field within the system of high power, cryogenically cooled coils.

2. Input documentation to start and realize activity

a. Type of analysis:
   - coupled electromagnetic-structural (multiple scenarios)
   - 3D,1/8th of model. Cylindrical (toroidal) symmetry condition – i.e. suitable condition mimicking the toroidal symmetry needs to be applied to all the faces that are defined by the cross-sections of the components and the poloidal cutting planes defining the 1/8th of the model
   - The model should allow changes of the part geometry, friction coefficients or electrical currents, these changes will be specified once the design and connected calculations within the main design team are optimised to a higher detail level and based on initial results achieved within this contract

b. Input files:
   - Geometry: detailed geometry will be provided in *.STP or *.CAT* files
   - Values of currents: supplied in text files

For the illustration of the problem complexity, the up-to-date toroidal segment of the tokamak support structure, coils and other relevant components is shown below.



At the end of this document, the short description of the individual components, list of contact types and material properties to be used is given.

In the Annex 2 of the Contract proposal, a *.STP* file with initial geometry is included for better understanding of the problem. This file is not intended to be used in the calculation; however, it represents the complexity of the problem sufficiently. **All input files will be provided at the signature of the Contract.**

The Calculation is supposed to consist of:

Phase 1

- calculation of Case 1 (Assembly) and Case 2 (specified EM loads)
- assignment will be provided by IPP at the signature of the Contract

Phase 2

- calculation of Cases 3-6, with different EM loads and/or coefficients of friction (to be specified)
- minor changes of the Support Structure design depending on the results of Phase 1 will be incorporated into the model
- assignment (EM loads) will be provided by IPP at the beginning of Phase 2 period as set up by the Contract

Phase 3

- calculation of yet-to-be-specified problem with extent of 120 professional hours (= 3 weeks)
- the assignment of the problem will be provided by IPP 5 weeks before the deadline, soon after delivery of the Phase 2
- examples of problems that may be assigned in Phase 3:
  re-calculation of specified Case with different frictional coefficients, detailed modelling of sub-assembly, change of sub-assembly and recalculation of specified Case, etc.

All delivery conditions (including delivery times and dates for specification of assignments) are specified in the contract for the work.

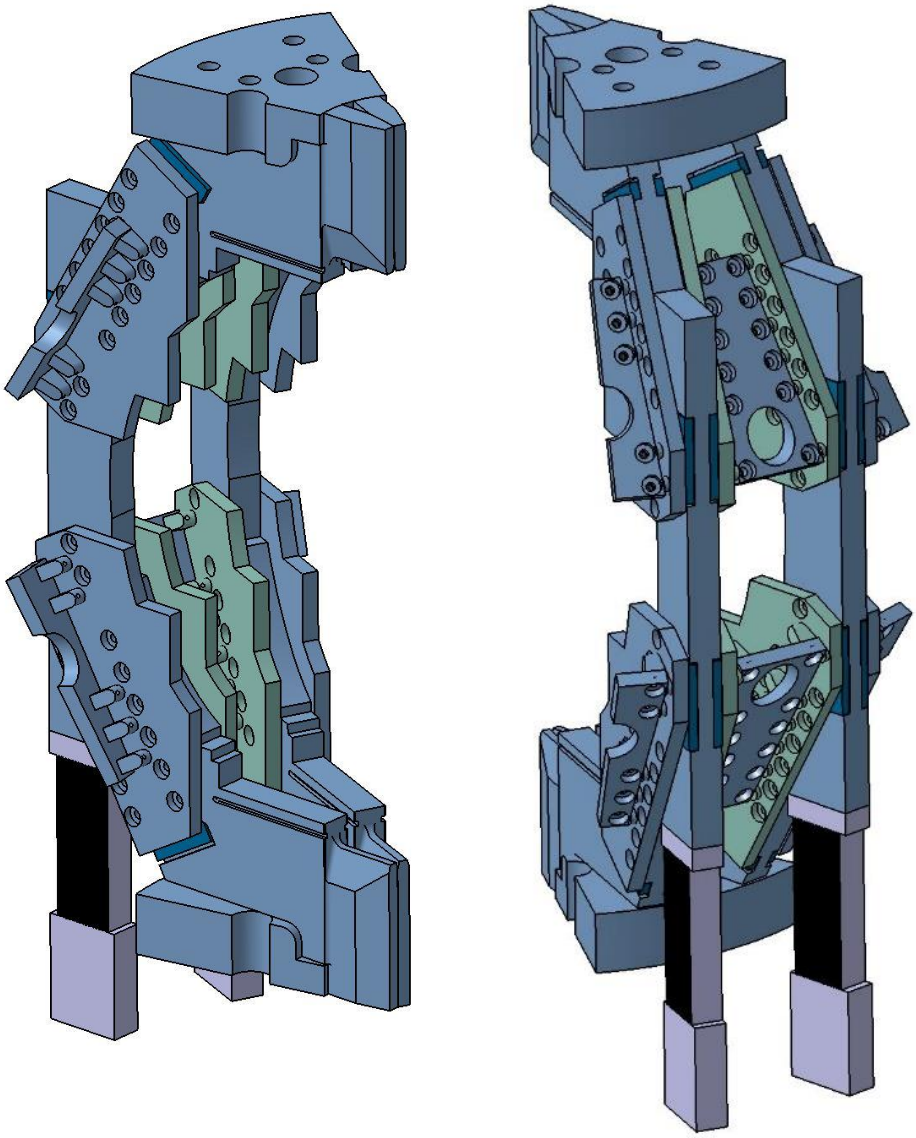
3. **Deliverables**
   a. Progress report summarising the calculations based on the initial input (Phase1)
      - Text document/self-descriptive slides in .ppt or equivalent
      - ANSYS result files
   b. Progress report covering the results of Phase 2
      - Text document/self-descriptive slides in .ppt or equivalent
      - ANSYS result files
   c. Final report withs results from all Phases
      - Presentation of results in English or Czech language
      - Results of the analysis provided in suitable form
      - Design, analysis and engineering recommendations
      - Please provide all files (.doc, .xls, .ppt, ...) constituting the report
      - Please provide all files (ANSYS 19.2, ...) constituting the modelling and results

Main components of the tokamak, boundary conditions, materials

Generally, the input geometry consists of these main components:

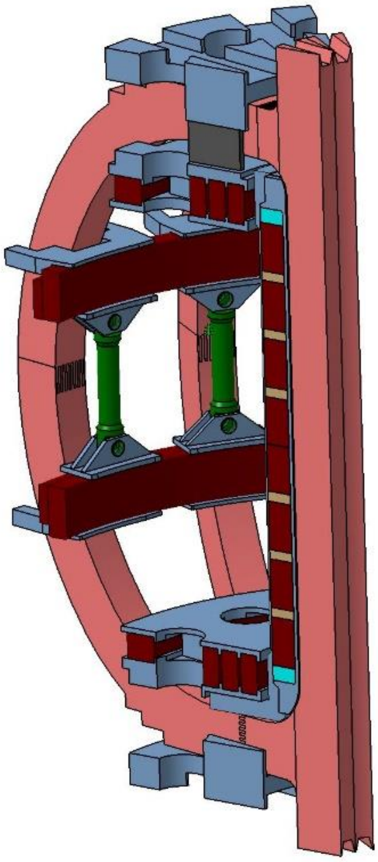
i. **Support structure elements**

mainly stainless steel with glass-fiber composite spacers and other small elements made of different materials. Holds the toroidal and poloidal coil system aligned with respect to each other and to plasma column. Must withstand radial, vertical and toppling (specific forces in toroidal direction) forces of large magnitude.



ii. Coils

Thick high current conductors, mainly OFHC copper enclosed in glass-fiber composite cover



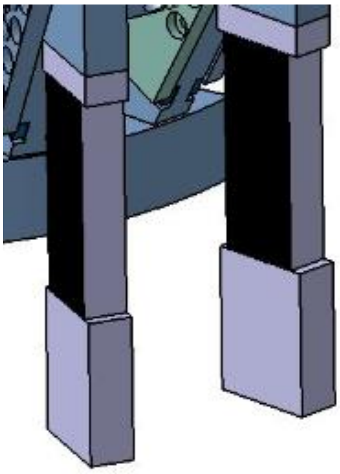
There are two types of coils:

- **poloidal field coils** (dark red in the picture above)
    - *outer* PF coils and *central solenoid segments*
        - ring shape, current flows in the toroidal direction
        - may be modelled as Cu ring monoblocks
- **toroidal field coils** (orange in the picture above)
    - D-shape, current flows in poloidal direction
    - will be modelled as Cu monoblock and with separate models of the bolted and sliding joints

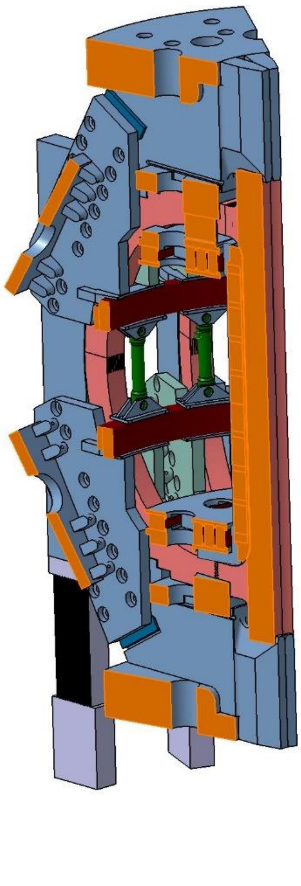
As indicated at the coil types above, it is possible to use equivalent material model for main body of both types of coils. Generally, do not use bonded type of connection (either copper to steel or epoxy to copper, etc.) but replace the material sandwich by equivalent material model.

Boundary conditions

- Each pillar of the support structure is standing on a flexible leg. The purpose of the leg flexibility is to allow the inwards (radial) movement due to the difference in the temperature. Tokamak structure will be cooled down to 77 K, this means that the legs will be anchored to the room temperature on one side and bolted to the device on 77 K on the other side. The flexible legs are be part of the model, in case of serious problems with the convergence they may be neglected.



- Planes of cut of 1/8th of the tokamak are supposed to have cylindrical symmetry condition. The faces where this condition is applicable are highlighted in orange in the picture below.



Contact specifications will be provided in the form of surface model. The contact properties are as follows:

1. **Frictional with the friction coefficient 1.5** (mainly steel to steel)

2. **Frictional with the friction coefficient 0.5** (mainly G10 to steel) - this contact will be used for torsional locking of toroidal field coils core by the so-called crown structure. In case of problems with this type of contact, frictionless type of bond should be used at G10 to steel interface.

3. **Frictional with precompression** - the friction coefficient ~1.5 (contact on electrical sliding contacts, pre-compression 2.5 MPa and 5.5 MPa). In case of problems it is possible to use a sub-model.

4. **Epoxy bonded Cu to G10**. In case of problems it is possible to use a sub-model.

5. **Bonded connection of flexible legs** to support structure

6. **Bonded or welded connection** - this is either G10 to G10 or expected weld on the steel structure

There are most probably some types of connection which will not be specified in the file and will have to be specified during the preparation of the analysis.

Material specifications are also provided for each component.

Material properties to be used (at 77K)

Material	**E [GPa]**	**Yield str. (0.2%) [MPA]**	***v***
Cu OFHC	136	275	0.336
AISI 304	205	494	0.28
Nitronic 50	200	983	0.31
Nitronic 50 high str.	200	1330	0.31
G10	E_x=29.5	G_{xy}=2.62 GPa	v_{xy}=0.18
	E_y=32.9	G_{xz}=14.62 GPa	v_{xz}=0.35
	E_z=13.8	G_{yz}=14.62 GPa	v_{yz}=0.21